National Aeronautics and Space Administration

YEARS 1-3 ***EXECUTIVE SUMMARY***

Scientific and Exploration Potential of the Lunar Poles

PI: Ben Bussey (JHU/APL)

NASA LUNAR SCIENCE INSTITUTE

Scientific and Exploration Potential of the Lunar Poles Executive Summary

PI: Ben Bussey (JHU/APL) ben.bussey@jhuapl.edu

When we began this integrated research project, the lunar polar regions were regarded as "*Luna incognita*", the unknown Moon. During the last three years we have striven to further our understanding of the polar regions so that they are now as well known, and in some case better known, than the rest of the Moon. *"Luna incognita*" has become "*luna cognita*".

The goal of our team was to advance our scientific understanding of the Moon's poles and to fill in strategic knowledge gaps that facilitate the robotic and human exploration of these areas. One aspect that could not have been predicted is the wealth of new data that have become available since we began. These new data produced by an armada of spacecraft, including India's Chandrayaan-1 and Japan's Kaguya mission, provide new insight into the processes and history of the lunar poles.

Characterizing Luna Incognita:

- *Study the geology of the poles*
- *Characterize the surface and subsurface properties*
- *Evaluate the ability to conduct surface operations, regolith excavation, and drilling*
- *Evaluate potential instrumentation for science conducted from and on the Moon*

A key aspect of our research has been collaboration. In addition to the natural collaboration between team members our work has benefited by the successful collaboration with other NLSI teams as well as other US and international scientists and engineers.

Our research has addressed several high priority science concepts from the SCEM report; "*The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history*", "*The bombardment history of the inner solar system is uniquely revealed on the Moon*", "*The Moon is an accessible laboratory for studying the impact process on planetary scales*", "*Key planetary processes are manifested in the diversity of lunar crustal rocks*", and "*The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies*". Additionally our work supports the goals of the Planetary Decadal Survey "*What are the compositions, distributions, and sources of planetary polar deposits?*"

Our research has been divided into three themes: (1) Lunar Polar Environment, (2) Surface Characterization, and (3) Surface Science, Instrumentation, and Operations. By design, there is substantial overlap across topics, with each providing information to the others to facilitate a deeper, more thorough understanding of the questions that are posed.

Lunar Polar Environment: This theme includes: geology, illumination, volatile transport modeling, volatile-regolith laboratory studies.

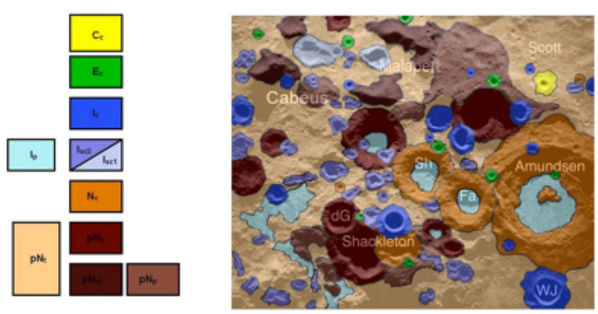
Lunar Polar Environment:

- *Study the geology of the lunar poles*
- *Characterize the polar illumination conditions*
- *Migration, sequestration and stability of polar volatiles*
- *Mechanisms of volatile storage*

Polar Geology: We have conducted several studies designed to elucidate the geological histories, nature and origin of the polar deposits. Using new spacecraft optical and radar images and Earth-based radar images, we have re-investigated and mapped the geology of the south pole, including a determination of the relative age of Shackleton crater. Shackleton was found to be more heavily cratered (older) than the mare surface at Apollo 15 (3.3 Ga), but less cratered (younger) than the Apollo 14 site (3.85 Ga). These data indicate that Shackleton is older than originally thought (Imbrian age) and may have collected extra-lunar volatile elements for at least the last 2 billion years. Such a history makes this crater an attractive site for exploration and possible human presence.

Polarimetric radar data acquired with the Mini-RF instruments indicate that ice may be abundant in the polar regions. Some craters show elevated CPR only in their interiors; over 40 of these anomalous craters have been identified. The radar signature is consistent with the presence of ice deposits in the interior of these craters. Almost all are in permanent sun shadow and correlate with proposed locations of polar ice modeled on the basis of Lunar Prospector neutron data.

In response to the assertion by the Augustine Commission that a return to the Moon is unaffordable, we investigated a possible architecture that extends human reach beyond low Earth orbit by creating a permanent space transportation system with reusable and refuelable vehicles. Such a system is made possible by establishing a robotic outpost on the Moon that harvests water and produces propellant from the ice deposits of the permanently dark areas. This outpost can be established under existing and projected budgetary limitations within 16 years of program start.

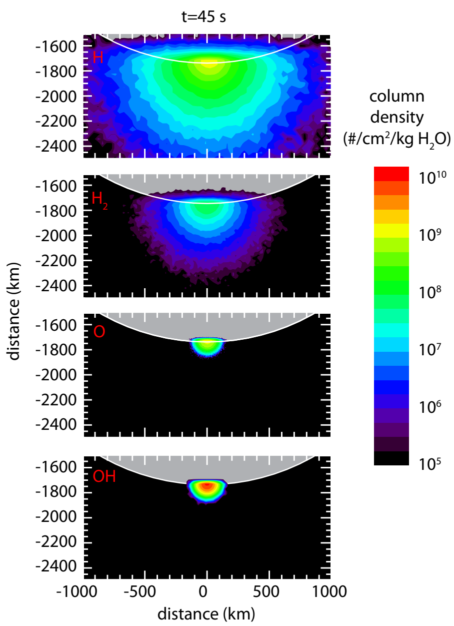


We have remapped the polar geology

Polar Illumination: The availability of high-resolution topography, combined with a high-fidelity simulation tool has allowed polar illumination conditions to be well characterized, including the ability to determine data useful for planning future lander missions. We have developed a simulation tool called LunarShader that uses topography data and a user-selected Sun position to precisely determine which areas of the lunar surface are illuminated. Our first milestone was a comparison of Clementine images with simulations using Kaguya's laser-derived topography data. Comparison between our simulations and the actual images revealed a very good match. Now that we have validated the results from the simulation tool we were able to map the illumination conditions at both poles, determining which areas receive the most sunlight, as well as mapping the areas of permanent shadow that never see the Sun. We have continued to improve our knowledge of these areas by using the higher spatial resolution products that have been released be LRO's LOLA team. As the spatial resolution improves, we find that the areas that receive the most illumination get smaller. We are excited by future collaboration with the LROC team, combining our tool with their NAC high-resolution analyses.

Part of our research has considered the affect of placing solar arrays on different mast heights. We have found that even engineering feasible mast heights of a few meters can result in increased Sun visibility compared with the surface illumination.

Polar Volatiles: Since our team was established, volatiles in polar regions have been definitively detected. Our research has analyzed data regarding lunar volatiles and conducted modeling to support interpretation of the volatile data. This work includes atmospheric modeling to consider volatile transport and space weathering to follow volatile retention.



Modeled photodissociated products of water in the LCROSS plume

The impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) into the crater Cabeus released water and other volatiles into the space, where they were observed by LRO, LCROSS, HST, and ground-based telescopes. We modeled the propagation of the vapor release and compared that to the observed light-curves for H_2O, OH, H, O, Na, H_2, CO, Mg, Ca, and Hg. For selected species, we determined the timing, temperature, bulk velocity, mass, and regolith abundance of the species. This study was not included in the original proposal; but arose from the interactions among our NLSI team members and the NSLI DREAM team after the success of the LCROSS experiment. We used two-dimensional modeling of space weathering processes on the Moon to provide a framework for interpreting spacecraft data regarding polar volatiles. We have simulated the evolution of an ice layer over time and compared the model results as they would be observed in neutrons, FUV, radar, and in situ. This work enables a self-consistent interpretation of the seemingly disparate data on the distribution and abundance of volatiles in lunar polar regions coming from LRO, LCROSS, and Chandrayaan-1.

Volatile-Regolith Modeling: Our team is conducting laboratory and modeling experiments to better characterize and understand the nature and evolution of H_2O, hydroxyl, and other volatiles potentially at the poles. We are conducting Temperature Programed Desorption measurements on lunar analog materials to determine the thermal stability of both molecular water and hydroxyl on the surface. We also characterize these adsorbed species with UV through IR reflectance measurements under appropriate pressure and temperatures.

We have identified a compositional dependence in the thermal stability of water on lunar analog materials, when that data is coupled to our models of water evolution, it affects our prediction of the distribution of water (and hydroxyl) on the Moon. Additionally, by experimentally and theoretically investigating the stability, formation, and loss of water and hydroxyl, we can understand better if/how solar wind may form hydroxyl and how this hydroxyl may evolve to form water. Our experiments to determine the spectral nature of adsorbed water and hydroxyl enable us to assign the infrared absorption bands observed on the Moon to water or hydroxyl, thus providing insight into the origin and nature of these materials.

Surface Characterization: We have been using the latest data to study lunar surface characteristics. We have determined that self-secondary cratering on the continuous ejecta is a significant factor during an impact event. Such self-secondary craters are in part buried by melt and bouldery ejecta facies indicating that they formed concurrently with ejecta emplacement. Since the lunar chronology is tied to the crater frequencies of the Copernicus and Tycho ejecta blankets, if those frequencies do not represent the impact flux, the chronology will be incorrect.

We have also discovered that impact melt can occur in simple highlands craters down to diameters as small as 170 m. These craters have been interpreted as due to vertical impacts wherein maximum shock and heating occur (compared with more oblique impacts). As vertical impacts are relatively rare, so are such small craters with impact melt.

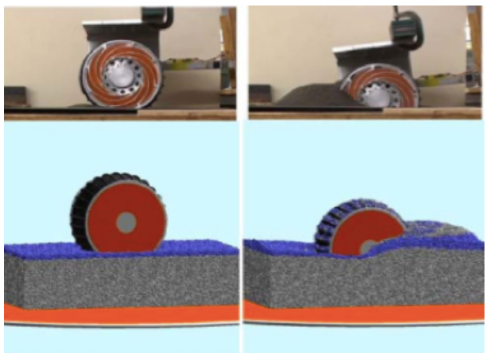
We have been examining the mineralogical composition and thermal history of low-calcium pyroxenes excavated from deep within the lunar crust. The composition and stratigraphy of these rocks provides key constraints on the nature and evolution of the lunar magma ocean. We have also been mapping the distribution of hydroxyl absorptions across the Moon, likely produced by solar wind bombardment of the lunar regolith. The OH^- production hypothesis is being tested by characterizing the volatile distribution on localized scales at different times in the Lunar day, to evaluate whether it is transient or stably distributed.

Surface Science, Instrumentation, and Operations: This theme consisted of diverse objectives with the common thread that they either uniquely use the lunar poles and/or are enabled by a lunar polar location.

Surface Science, Instrumentation & Operations:

- *Mobility & Excavation Studies*
- *Use of Ground Penetrating Radar*
- *Neutron Studies*
- *Earth Observation*

Excavation & Mobility Modeling: The goal is to develop physically based discrete element method (DEM) models of excavation and mobility problems on the Moon. The effects of different gravity, soil types and physical processes on the Moon, asteroids, and other planets make it impossible to accurately predict machine performance from Earth-based tests alone. We have: (1) conducted physical testing of wheel digging, static and percussive excavation, penetration, and geotechnical tri-axial strength tests on lunar simulants (primarily JSC-1a); (2) developed DEM model capabilities; (3) validated model capabilities by simulating physical tests using the models. Our most significant achievement is the development and validation of a physical DEM and distribution of its beta version to Glenn Research Center and CRREL for testing and use in simulating physical tests. While the DEM was developed for excavation and mobility applications, its design is sufficiently general that it can be applied to other important lunar and small body problems, such as volatile migration in lunar regolith, and asteroid properties. Other accomplishments include developing extensive physical test data related to excavation and mobility and lunar simulant mechanical properties.



We compare physical testing with modeling results.

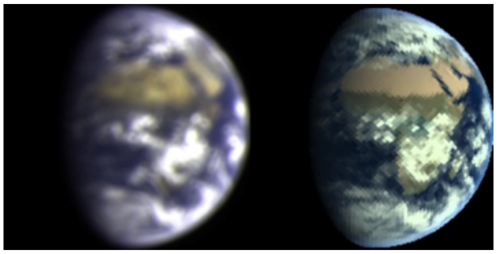
Ground Penetrating Radar: Ground-Penetrating Radar (GPR) data from terrestrial analog environments can help constrain models of the evolution of the lunar surface, help predict the nature of subsurface properties, and aid in interpretation of orbital SAR data. GPR data from terrestrial settings can constrain the range of expected radar properties associated with varying substrates, thereby providing a tool for predicting the physical properties, clast-size distribution, and layering of the lunar subsurface. The goal of our work has been to demonstrate the capabilities of GPR in defining the range of radar properties at terrestrial sites where geologic processes, settings, and/or materials may be similar to those encountered on the MoonFieldwork has been conducted at five planetary analogue sites; Meteor Crater, Sunset Crater and SP Cone cones and lavas, the Columbia River Plateau basalts, and multiple locations on the Big Island of Hawaii.

By comparing analysis of GPR with the known local stratigraphy, we have shown that GPR can be used to probe the subsurface and help constrain the physical properties and setting of near surface materials. Our work highlights the utility and portability of using such a GPR during future exploration on the lunar surface to map geologic environments and target locations for sampling and suitable for eventual human exploration.

Neutron Studies: We have focused on: 1) Determining the feasibility for making high spatial resolution neutron measurements on the surface; and 2) Carrying out neutron transport modeling and data analysis to test ideas about measuring lunar hydrogen abundances. We studied the design of a surface high-resolution neutron imager using two different technologies, collimated and grazing incidence. Our analysis shows that a collimated instrument is required to collect such measurements.

Recent spectral data have shown the presence of surficial water over large expanses of the lunar surface. These results have led to a reexamination of the hydrogen abundance sensitivity limits of orbital neutron data. A wet-over-dry, two-layer stratigraphy has been modeled for the first time using neutron transport codes. Application of this effort to Goldschmidt crater reveals that it may have an enhanced hydrogen content of 0.1-1% water equivalent hydrogen. We have also studied data from the Lunar Exploration Neutron Detector (LEND) in order to better understand how these data provide information of lunar surface hydrogen abundances. We have confirmed that the LEND instrument is sensitive to lunar surface compositional variations from both the collimated and uncollimated sensors.

Earth Observation: Our goal is to examine the potential for a long-term full-disk Earth observing instrument on the Moon. The intent is to develop an instrument concept to characterize the remotely detectable physical and biological signatures of the Earth as a function of time. A lunar polar vantage point is unique, making it possible to track Earth's ever-changing photometric, spectral and polarimetric signatures in a manner analogous to future observations of terrestrial planets orbiting other stars.



Comparison between LCROSS observations and model results

The work includes: the appearance and spectroscopic signatures and polarizations of the Earth and the strength of circular polarization signatures from biological material. Though not part of the original proposal, we fostered a collaboration with the LCROSS team to utilize their spectroscopy and imaging (UV to mid-IR) of the Earth at three very different orientations and phases. Sophisticated and detailed models have been produced by the NASA Astrobiology Institute Virtual Planetary laboratory for the Earth covering the three LCROSS Earth observing epochs. We find a good correlation between the actual and modeled results.

Education & Public Outreach: Conveying the excitement of studying the Moon to the general public is an important aspect of our work. The EPO effort for our NLSI team continued to promote lunar science education through formal education and public outreach activities. Formal education activities included middle and high school educator professional development and a higher education lecture series. For Public Outreach, NLSI collaborated with the Maryland Science Center to host an event for International Observe the Moon Night. Also we maintain a website that reviews current lunar research done by NLSI and video archives of NLSI lecturers (http://lunarpoles.jhuapl.edu/).

The "Unknown Moon Institute" workshops are a professional development opportunity for middle and high school educators from around the country. During this five day workshop, teachers receive in-depth content and participated in rich inquiry-based activities about lunar science. As part of our EPO effort we have developed a Lunar Geology Map lesson (that has passed SMD Product Review) that presents a discussion of types of geologic features found on the Moon.

NLSI
Lunar Polar
Science & Exploration